Process control- design, analyses and assessment
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Traditional Advance Control-part 6

Let us continue with our 28th lecture in this course looking at more advanced topics in process control.

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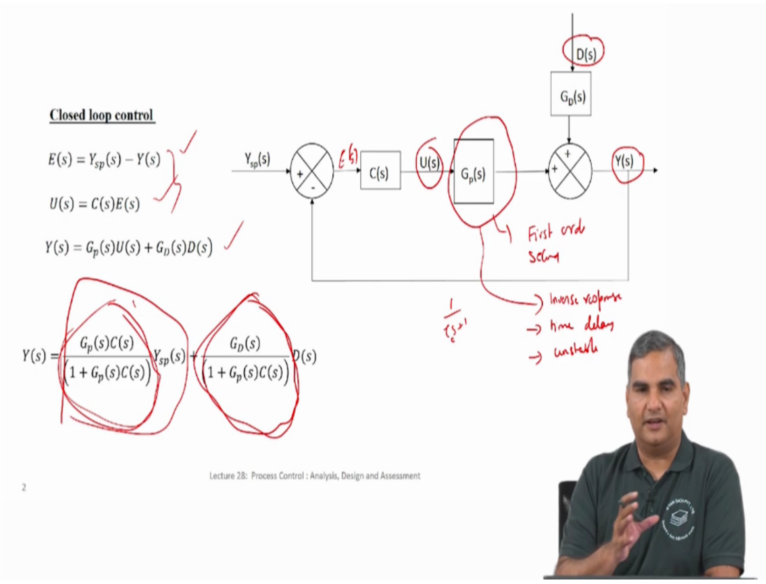

Just as a quick recap for the kinds of things that we have seen till now, this is a traditional feedback control loop and we have discussed this in a considerable detail till now. So as a recap this output, a measurement our output is going to be affected by both the input and the disturbance easily we said Y of s Gp s Us plus GDsDs and then when we want this output to do what we want in terms of following a set point or whenever there are disturbances we want the output to maintain its value, these are the 2 types of controllers that we talked about.

The first one is called the servo control, the 2nd one is a regulatory control, we close the loop. And the idea of closing the loop is looking at the difference between the set point and Y. And then use that as an error signal to a controller and that error signal, the controller acts upon to give a input to the process. Now if this error is zero either the Y set point being changed but Y change because of Ds but now it's brought back to its original set point.

Or in the case of servo control Y set point itself changed and Y is being drag to get to the value of Y set point whenever this error is zero. So when this error is zero I don't have to take any control action but as long as there is an error I keep taking control action to set it to 0.

That way disclose loop works for both the disturbance rejection and following set. Now clearly the beginning of the source we started with a prime domain understanding of the process and so on.

And then we said if you use Laplace transforms it becomes very easy to analyze these systems, so that's a reason why we did Laplace transforms and once you do Laplace transform closing the loop and analyzing this system just becomes a question of looking at algebraic manipulations and we actually saw that for this close loop if you did simple algebraic manipulation by just writing down the equations.

Here U of S, C of s times C of s, E of s is Y set point minus Y, so that is one equation here and here. And then Y of s is simply GD of s D of s plus Gp of s U of s that's our very equation. Now what you can do is, from these 2 equations you can write U of s as a function of the controller and set point and then do some algebraic manipulation and then you will basically derive in closed loop what happens.

And we see that in closed loop I have this transfer function which is related to the servo control and this transfer function which is related to the disturbance control. Now after doing this we looked at how you design a controller. We talked about PAD structure P is for personalized integral D derivative and then showed how the controller parameters could be tuned.

And then we said tuning could be of 2 types one is stability based where you try to push the system in a closed loop with a P controller to as close to the stability limit as possible and then basically back off from there to actually give the detuning parameters. The other approach we said was what is called a direct synthesis approach which is to say look I have this closed loop function here.

And ideally they should be one in which case Y s will be just Y s to set point S but that is simply not possible, so I'm going to use the simplest approximation to 1 which is something like 1 by Tao closed loop s plus 1 and then once I know what I want this to be I can back calculate controller c of s which is the idea of direct synthesis. Now we talked about direct synthesis purely from the viewpoint of servo control.

Now all of these ideas are also directly translatable had to the disturbance rejection also. Supposing you want to focus on disturbance rejection and then you want to have a particular form for the disturbance function model you could use that and then say okay, this is how I want my controller to be designed and so on. Be focused on this closed loop and I already showed you that whenever this works well this also will work reasonably well.

Remember the P controller example we talked about where if we keep pushing the controller gain larger and larger this will go closer and closer to 1 and this will go closer and closer to 0 which is what we want. This should go closer to 0 because we do not want any impact of disturbance on the output or minimize the impact of disturbance on the output in a close loop, so all of this this we saw.

After this was done once we understood direct synthesis then we said okay let's look at what are the complicating dynamics that that we can look at in terms of this GpS till that point we looked at simple first-order systems then second-order system and so on. And you can expand this to 3^{rd} order and 4th order and all that, so the order of the system is basically the order of the denominator polynomial, so this is also something that we saw.

And then once we understood all of this then we said what type of complicating dynamics could be there in Gp of S we talked about 3 different types of complicating dynamics which is, one is a inverse response the initial direction of change is different from the final value the output takes. We talked about time delay where it takes a certain amount of time before the action takes place.

And the last thing was, what happens if this Gp itself is unstable can I design controller, so that I make the close loop stable. So for each of this case now we have a good understanding of how the controller design should be done using a direct synthesis approach and how do you get a PAD controller after you do this direct synthesis approach, so all of this we have seen, okay.

Now as we go forward in this we are going to be reliant on a model more and more which is a point I already made and you could see for the first time in time delay system you actually use a model while computing the input, so we are going to explicitly use the model in controller computations also that's one thing we are going to see.

The other thing that I would like to show you in the next few lectures is to see what are the basic modifications that can be done to this loop itself in terms of adding more elements in the loop that will make control better? So now that we have seen for this basic loop all kinds of complications and how to address those complications we are comfortable with that. Now is there a way in which we can think about adding more elements in the loop in some cases for some reasons that will make it better from a controller viewpoint that's the kind of thing that we are going to talk about.

So in the next few lectures I'm going to first act with what is called cascade control which is kind of modifying this loop a little bit more, so that we can do better and better. And I will explain a situation where cascade control will be very very useful. I will follow that up with what call as a feedforward feedback controller again making some modifications to this blog diagram, so that you make the control better.

And then I will show you multivariable case of expanding this loop let's say to 2 variables at a time 2 inputs and 2 outputs and show you how one can generalize this idea of feedforward control to what is called as a decoupling control and that idea will explain with 2 by 2 multivariable system. So that will be the first time we will actually look at a 2 by 2 system in a blog diagram form more fleshed out blog diagram form like this this course.

And you will see how this notion of feedforward control can be thought of as a forerunner for this decoupling controller and look at expanding the single loop to let's say 2 loops at the same time which are interacting, how do you make them interact in ways that are favorable from a controller viewpoint and once we do that then basically understanding control and learning control within this frame (())(9:01) feedback blog diagram controller idea will be done.

We will then go on to what is called model predictive control where the controller itself is going to be directly computed based on model predictions and there is going to be notion of online optimization for computing the control moves, okay. So that is a model predictive control with that we will kind of finish these more advanced topics in process control.

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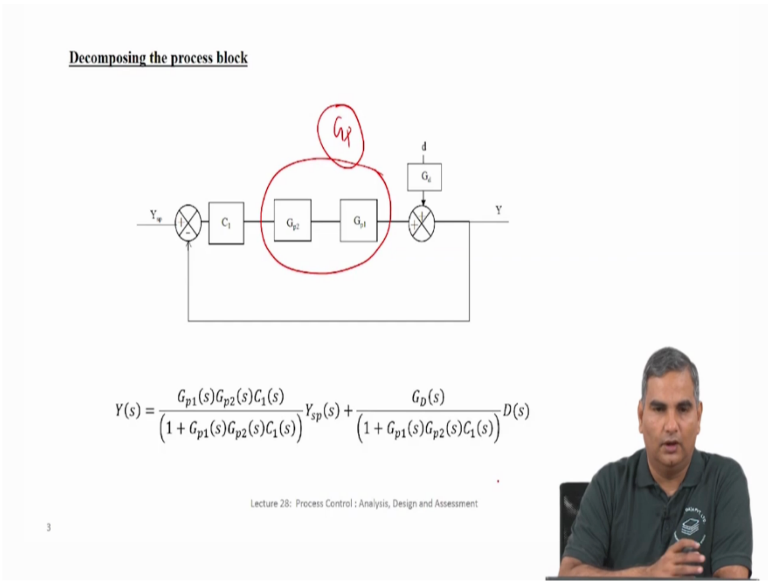

Now, so as I said before I'm going to add more details to this blog diagram and you have to remember that if you are adding more details to a blog diagram you should have more information that can be used by this details. So if I don't have any more information then what I have in terms of just a control variable and an output there is no point in expanding this diagram.

Because this expansion has to be in response to some extra information that we have and let me explain what I mean by that here. In the previous picture we had both of these together as Gp, okay. So let me take an example of how this works. So let's take simple flow example I'm going to draw a very very simple chart picture here to kind of look at a flow control loop.

And then explain what we mean by this Gp and how I can break this down into smaller blocks are distinct blocks and that talk about how I can use this notion of this distinct blocks in controlling certain systems better, okay. So that's what we will get in the next slide.

For now if you assume that there is some more information that allows me to break this G of p into this Gp1 and Gp2 and I can use that information to better the control I am trying to see how I can add more structure to this close loop, so that the control becomes better. So now what I have done here is, I have done nothing other than simply rewriting the close loop transfer functions by simply replacing Gp by Gp one times Gp 2 that's all I have done.

So in the previous slide I have Gp Cs divided by 1 plus Gp Cs and GD by 1 plus GpCs. Now that Gp I replaced it by Gp1 Gp2, so I am saying that process block itself I can write it as a multiplication of 2 blocks, okay. So when would this be useful and when would this happen.

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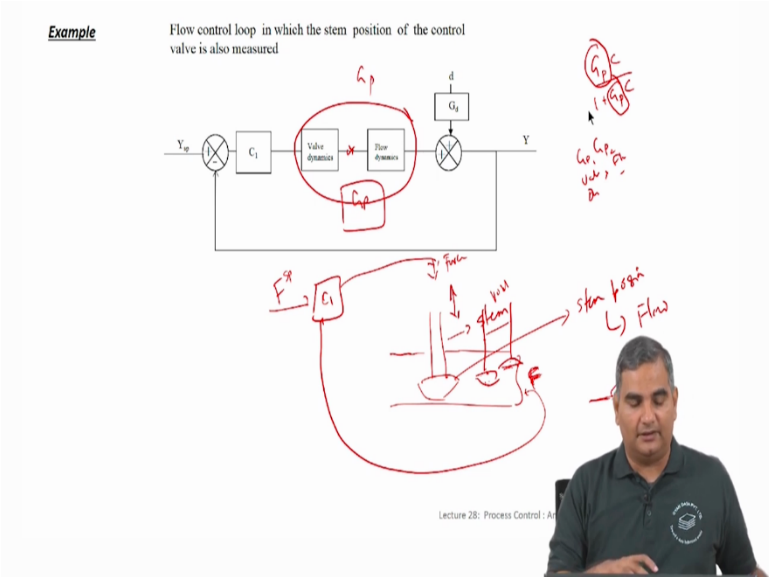

So, so the idea is the following. Let's take a flow process, now if you are looking at controlling a flow out of a pipe, so I'm just going to draw a diagram here for you to understand the basic idea behind what we are talking about here and a valve design and so on itself is little more sophisticated and there are different types of walls that you can use and so on.

But this is just to give you an idea of how this flow control occurs and then what it means when I use only one block for this and what it means when I use 2 blocks for this. So if I think about a flow control, okay. So I have this pipe, let's say I am looking at the flow out of here. The flow control is done by usually using what is called a control valve, okay.

And the control valve let's say something like this and then, so when you kind of move this up and down the amount of constriction that comes about in this pipe changes, so if you pull this out completely you will have complete flow, if you post this in completely you will completely shut down the flow and depending on what location you have in terms of the stem, you are going to get different flow rates that's how flow is controlled.

Now, so when you have a controller, okay. So there is a controller here, so let's do the controller here, so what the controller just is, it takes this value there is an instrument measurement instrument which measures this flow value and then it is going to cut a flow a setpoint that you are interest rate in maintaining and that it sees the difference and then based on the difference it gives a control action.

So the control action again like I said this is just to illustrate this and make you understand in the simplest possible way. The actual mechanisms can be different based on the different configurations. You can think of this as basically applying a force on this or relaxing a force on this, so that the stem moves up and down, right? So if you want zero flow then you have to apply in a force, so that the stem goes down and completely blocks the pipe.

If you want complete flow then you completely relaxed this flow, so that this goes up all the way out, okay. So basically the controller output is kind of, you might think of it as a force that is given to the system and for it to push the stem up or down, so that the flow is regulated or controlled, so this is your standard. Now if you think about this then this I can of together because there is a stem that is moving and there is a dynamics with respect to the stem moving itself.

So basically there are 2 things that are happening that you want to notice. Number one is the amount of blog based on the stem position, right? So I have a particular stem position, okay which is either down or up and so on. Based on this stem position there is a flow that is fixed, so supposing I am let's say I am at this stem position and then I go to this stem position.

So there is a flow rate that you expect when the stem position is here more block, less block those are the 2 flow rates but as soon as I moved from here to here the flow does not change immediately, so there is a dynamics that is associated with this. So whenever the stem goes from here to here maybe the flow has to increase from here to here but there will be a dynamics which will be associated with this, so okay. So this is what is called the flow dynamics, okay.

Now also notice that when I apply a force here, so the force if I apply a certain force, let's say the stem position is this and if I apply certain other force the stem position is this, so when I go from this force to this force it doesn't mean stem will go from this position to this position immediately, there will be some dynamics between that force and that stem position, right?

So it will take certain amount of time once I changed the force for the stem to move. So when you think about this whole low and you think about the controller the error between the Y set point and Y is driving the process in terms of a force, right? Which is applied on the stem and before you see a change in the flow rate in response to our control action there are 2 different dynamics that operates.

The first dynamics is actually the force to the stem position which is called the valve dynamics and the second is the stem position to the actual flow that comes out of the pipe, okay. So there are these 2 dynamics and clearly once you apply force then the dynamics has to take in account and push the stem down to a particular position and then once that position is reached then the flow has to react to the change in this stem position and then the flow will change.

So both the dynamics are important and typically you will have this valve dynamics precede the flow dynamics and in general if you don't even measure anything here in terms of where the stem is and so on then the only information you have is a force you apply and the flow you see here, okay. The fact that the force is applied the stem moves and based on the position of the stem the flow changes and so on.

While it happens you have no information about that, so that's a reason why what we typically do is, we have only are Gp and we basically assume that we don't know what's happening internally but we do an experiment where change the flow change the force and see how the flow changes and based on this change become up with a dynamic model which basically directly relates the force that you exert to the flow that you see.

So that Gp will subsume both the valve dynamics and the flow dynamics together, okay. So this is your standard system. Now the difficulty with this is the following, so now if we do not measure anything more there is nothing more you can do but one of the problems that even notice right away is the following, so typically let's assume the valve dynamics is much faster than the flow dynamics.

So let's say you want a certain flow which basically means that I have to move the stem to a certain position and remember I said no model is perfect. So I cannot exactly know what stem position is, right? The model predicts, if you are here and there is a certain flow and if you go here and there will be certain other flow that is just a prediction. So what do you will exactly get here will be slightly different than depends on the 2 process sensor function and so on.

So the key idea being, if you want to get a particular flow here basically let's say you give a force and then the only way which where you can figure out whether you have got the required flow is by looking at this flow rate and if this is very very slow dynamics then what will happen is, it will take you a long time before you figure out that you should have moved your stem a little more and so on, okay.

So in some sense what will happen is, you cannot speed up the process any more unless you bring in someone measurement, okay. So basically you have to see a change here before you make a change here and you get to a stem position but now let's say there is some problem with this part here. This stem was supposed to go somewhere but it actually didn't go there that again you cannot infer any other way other than by seeing the flow change, right?

So the flow didn't change as much then you will go back and put this force more force or less force and then this stem will move and whether the stem has gone to the right position and so on we will only figure out after we measure the flow, so in other words I'm restricted by the dynamics of both the valve and flow in terms of how fast I can do this control and in some cases you know might be not happy with the closed loop performance.

To get when you simply make all your judgment for what force applied based on flow which is at the last step, right? So the question is if I'm unhappy with the performance, in other words if I keep increasing my gain till it becomes unstable that restricts the performance I get and I look at the performance and then say this performance is still not good enough for me to work with.

So, is there some way in which I can change the performance or make my closed loop even faster. So currently there is no way of doing it but if you add more information, okay. So what does that more information mean, supposing you said okay I am also going to make measurement of this stem position, okay. So I have a force then I actually measure where the stem has gone to, okay.

Now there is a way in which I can add more details to this closed loop to make this better, so this idea of adding more detail through this and cascading the controller instead of just one controller is a notion of cascade controller. So here the idea is the following, so what we are going to do is, if I don't measure the stem position I don't have a measurement here in which case I just put one GP here which is a combination of the valve dynamics and flow dynamics and I cannot do anything other than the standard closed loop.

Supposing I have a measurement here, okay. Now remember my closed loop transfer function is GpC by 1 plus GpC and this Gp is I told you Gp1 Gp2 which is in this case the valve dynamics times the flow dynamics, okay. So if I don't have any measurement here basically this is the best performance I can get, since this is the best performance I can get I have actually designed the controller for this best performance.

Now the question is, if I want to improve my performance I'm not happy with it what can I do, somehow I have to change their Gp, okay. So the minute you have to change a process transfer function in this case then you have to do some measurement, some hardware change otherwise we cannot do this.

In Cascade control you do this in a particular way, so I'm going to show you what the cascade controllers and please watch how this GP will change and I have some handle over what the GP itself is after I do the cascade control. So conceptually what this really means is that. Now I'm unhappy with the performance GpC by 1 plus GpC after I found the best controller that is possible.

So if I want closed loop performance I cannot do anything more to the controller because for this Gp I have found optimal solution. So the only way in which I can improve the performance is actually changing GP itself. So I should have some knob or a tuning way of changing GP, how do I get that is what cascade controller does and if you want to change the process transfer function.

And this is a kind of idea that comes up more advanced control where if you have your standard design and then you design a controller and you're not happy with that controller performance then the only way in which you can improve the controller performance is through what we call as redesign, so you can redesign the process or in this case we can redesign certain aspects of the process by adding little more hardware and measurement.

So any time you redesign the process basically you are either adding, subtract hardware and also adding more measurements. So the whole field of, how do you do this design changes, so that your system becomes more controllable is much more advanced idea and control but cascade control gives brief and very interesting look into this idea while being very relevant from a practical application. There are many cascade control structures in industry, okay.

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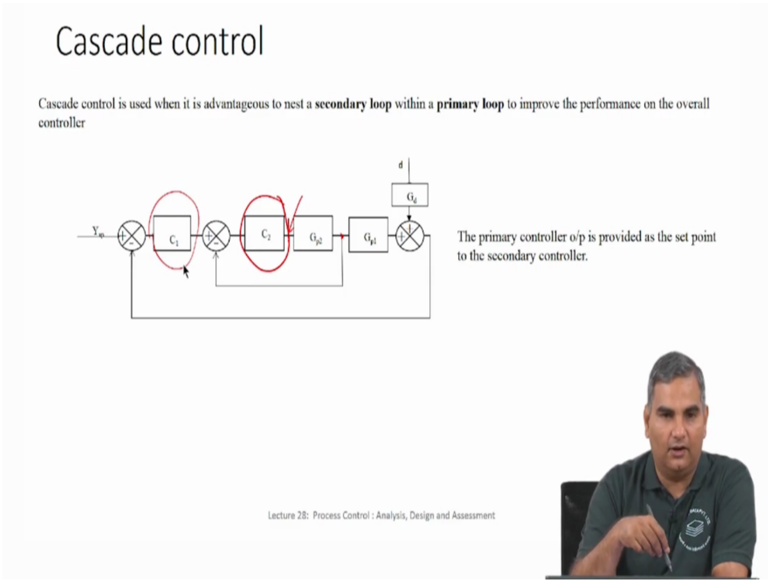

So basically what you are going to do now is, you remember the last slide I said Gp 1 and the Gp 2 there is no measurement in the middle then I cannot do anything I have to simply measure this and then go back and compare it with a setpoint but if I add a measurement here, okay Which is basically in the valve case stem position. So basically there is a force there is a stem position in the first case I didn’t measure I only measured the outlet flow rate and then saw how the force affects the outlet flow rate.

But if I actually measured a stem position then what you can do is you can give a set point to the stem position and (())(24:32) use another controller, so that this controller basically looks at the set point between the stem position and now since I have a measurement I can compare that measurement against the set point and then close the loop inside, okay. So there is one inside loop and another loop outside.

And this inside loop is possible only if I’m able to measure the output of the valve dynamics which is the actual position, right? So now if I am able to do this then what I can say is, let me introduce another controller C2 here and then this becomes the inside loop and there is an outside loop which is already there. So this is what is a cascade controller there is the inner which cascades do and outer.

And if you look at this blog diagram come back to the one before there are 2 controllers that we have and in the previous case this Gp1 measurement out of this Y went with the Y set point and the controller said what should be the force that we should keep. Now this controller is going to do something different what this is going to say is, this is going to say instead of what force that should be kept.

This is going to say what is the stem position that should be kept, so it becomes the setpoint to the secondary or inner loop and once this position is measured that position is checked against whatever is the setpoint and then now this controller will use that information to say what force should be kept here, so that the position is gain. So the force comes here, in the previous case only I had Gp.

The force came right after C1 but the force comes after C2 whereas C1 gives a setpoint to this internal controller, internal closed loop which is to say what should be the stem position. So that is the basic physical idea of this cascade controller. So the outer or the master controller whatever you want to call it gives a setpoint to the, that can be your inner or a slave controller.

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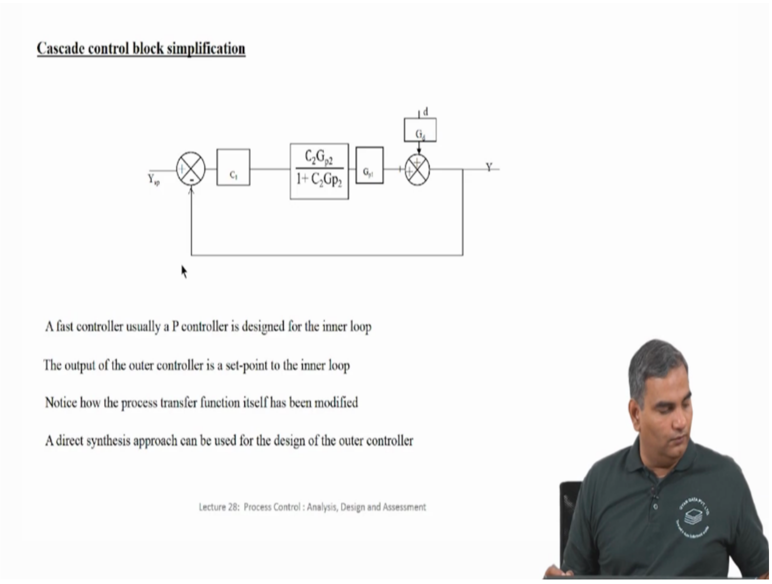

So now we have this, so what happens now in terms of analyzing the transfer function? So what I'm going to do is, I'm going to show you this idea that, okay.

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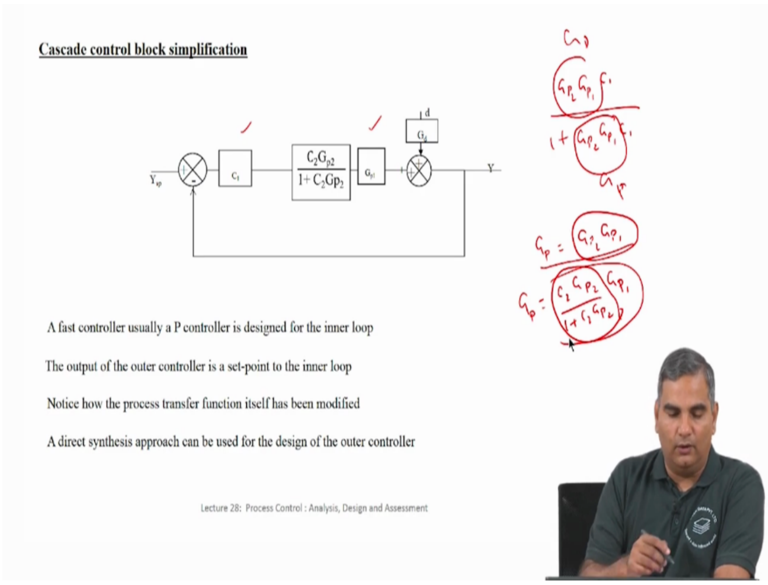

So how do I come back to my original simple blog diagram? So the idea is the following remember in one of the previous lectures I said, okay. So if you take this part, okay at this point at this point, this is where some new structure has been introduced some new complication has come in. So what I want to do is, if I want to come back to my standard structure of how this control loop looks then basically what I want to find out is.

I want to find out what is a transfer function between this point and this point then what I can do is, I can simply put that transfer function block here and then make it look like my standard closed loop block and I have already said if we have a closed loop, if you want to find the transfer function between any 2 points within these closed loop then you go from here to here multiply all the blocks that come in the forward path.

In this case the blocks that come in the forward plot or C2 and Gp2 and then the denominator is 1 plus all the blocks that take part in the loop and if you go through this loop the transfer function that take part in this loop are only C2 and Gp2, so this will be one plus Cp2 Gp2, so this whole substructure within this I can replace it by C2 Gp2 divided by 1 plus C2 Gp2 which is what you see in this diagram.

So C1 still remains, Gp1 still remains and now it has become C2 Gp2 divided by one plus C2 Gp2. Now what did we gain by all of this, okay. So if you ask that question and say we did all of this what is that, that we have gained. Notice something very interesting that has happened here I started by saying that if I didn't do this measurement and so on I'm going to, so I said if we are not going to do any measurement and so on.

Basically I said the closed loop transfer function is going to be Gp2 Gp1 times C1 divided by 1 plus Gp2 Gp1 times C1 and then Gp2 and Gp1 are known I have found the best controller for this and I'm still not happy with the closed loop performance, what do I do? Okay. So this is basically originally was Gp. Now what we have done is, now this Gp because I got that extra measurement has been converted to Gp 1 times.

So now initially what was Gp was Gp2 Gp1, now because of the cascade controller this Gp has become C2 Gp2 divided by 1 plus C2 Gp2 Gp1, okay. So we started by saying, when I had this GpC by 1 plus GpC and I found the best controller and still I am unhappy with the performance then the only thing that I can do is change Gp, so initially Gp was Gp2 Gp1. Now notice how I have been able to change this Gp to C2 Gp2 divided by 1 plus C2 Gp2 Gp1.

So in other words the desired that express was that I should have some tuning knob to modify the process transfer function now if I think of this as overall process transfer function at least a part of it now I have a tuning knob to modify, so that this overall thing will be different from here, okay. So by doing the cascade control I have somehow inserted a tuning knob so that I change my process transfer function itself.

So that I get performance that is desirable, right? So instead of just living with Gp1 Gp2 C divided by 1 plus Gp2 Gp1 C as my performance. Now because I am able to modify Gp itself with a tuning knob that I have I can actually tune this to get better performance. So in the previous case once I have the best controller I cannot do anything more. Now what I can do is, since I have change the process itself that gives me first better control.

And for this process I can look at another controller which will give me performance that is acceptable to me, so that is a beautiful idea of cascade control in terms of how you modify the process transfer function itself but to modify the process transfer function you have to add more measurements and add more hardware to be able to do this, okay. Now once you have this diagram it is very simple.

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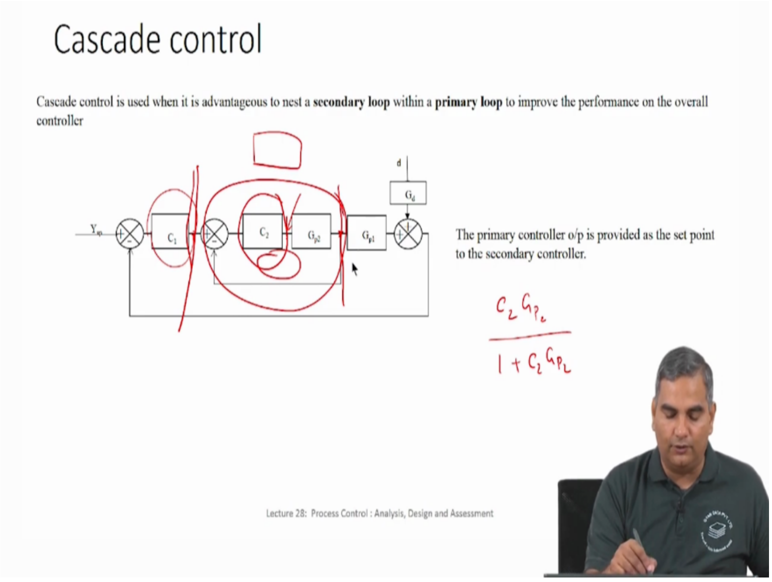

Usually what you do is, the inner loop that is here you first tune and this you tune using a simple p controller because it is fast it is efficient and also remember ultimately there is another controller outside. So if you put a PA controller here you can get rid of offsets and so on. So you do not have to really worry about offsets in the controller inside.

The only criteria we are looking for is that the controller could be fast, so typical P controller is good enough for the inside controller, so once you design the inside controller then you can actually compute this now your transfer function becomes C2 Gp2 by 1 plus C2 Gp2 times Gp1 this model for this you know, model for this you know, this is a controller you have define yourself which is just a constant.

Now for this process now you could use any technique to desire a controller. You could use Ziegler-Nichols tuning, you could use Cohen-coon tuning and so on or a direct synthesis approach to design this controller and this modified transfer function, okay. So the first controller is a simple p controller make it fast and once you do that you have this modified transfer function model which they gain you can use everything that we have learned in terms of controller design.

So you can either use Ziegler-Nichols, Cohen-coon, IMC based tuning you can do some direct synthesis from that you’re interested in and then you can tune the outer controller. What this would do in terms of physical system is, if the inside dynamics, valve dynamics is particular rate without closing the inside loop by closing the inside loop what we are doing is, we’re making the valve dynamics faster, right?

Because the typical idea for controller is to make sure that your closed loop dynamics is faster than your open loop dynamics. If I didn't do a measurement of the stem position and then close the loop I have to live with the normal valve dynamics but because I do a measurement of the stem and close the loop I can now have valve dynamics which is faster than normal which will help the overall control of the system.

Now if you really make it really fast that the minute I have a set point for a stem position I go there clearly the dynamics is then only dictated by the stem to the flow and that we are not doing anything about we are only minimizing the effect of this valve dynamics by making that faster from a closed loop viewpoint in this case. So notice how by adding a measurement and thinking about this in terms of tuning knobs for modifying the performance of the control loop we are able to come up with this control structure call cascade control.

And also see how using the same rule where between 2 points if I want to transfer function I will take the forward path and then do this one by 1 plus all the transfer functions in the loop as way to reduce the transfer function between 2 points which as a sub structure one block and then we put that into the same structure that we are comfortable with and then once we get the structure than Gp is just a multiplication of this too and everything that we have learned till now can be used in tuning this controller.

So this is the basic idea of cascade control and as I said before this cascade control is used quite a bit in process industries, so that you can get performance that is really acceptable from the viewpoint of your objectives for control. So this is the first time we have seen how to add substructures to this loop. Another way of adding substructure using feedforward control is something that I will talk about in the next lecture, thank you.